I. Radiation

Four types of radiation are discussed:

- Alpha (α) – $E_{max} \approx 20$ MeV
- Beta (β) – $E_{max} \approx 10$ MeV
- Gamma (γ) – $E_{max} \approx 20$ MeV
- Neutron (n) – $E_{max} \approx 15$ MeV

This radiation with the quoted maximum energies is encountered around nuclear reactors, around installations involving production or use of natural or manufactured radionuclides, and also around low energy accelerators.

Alpha particles:

- The alpha particle is a helium nucleus (2 protons, 2 neutrons) produced from the radioactive decay of heavy metals and some nuclear reactions.
- The high positive charge (2+) of an alpha particle causes electrical excitation and ionization of surrounding atoms.
- Alpha particles are the least penetrating radiation featuring a relatively straight path over a short distance (several cm in air).
- The specific ionization of alpha particles is very high.

Beta particles:

- There are two types of beta particles: electron (β^-) and positron (β^+). These are ejected from the nucleus of a beta-unstable radioactive atom ("neutron-rich" and "neutron-deficient" or "proton-rich" nucleus, respectively).
- The beta has a single negative or positive electrical charge and very small mass.
- The interaction of a beta particle and an orbital electron leads to electrical excitation and ionization of the orbital electron.
- Beta particles follow a tortuous path (zig-zag).
- The specific ionization of a beta particle is low due to its small mass, small charge, and relatively high speed of travel.
- The interaction of β^+ (positron) with an electron leads to their annihilation and occurrence of two annihilation photons with the energy of 0.511 MeV.

Gamma rays:

- The gamma ray is a photon of electromagnetic radiation with a very short wavelength and high energy.
- Gamma rays are emitted from unstable atomic nuclei and have high penetration power.
- The specific ionization of gamma is low compared to that of an alpha particle, but is higher than that of a beta particle.

Neutrons:

- Neutrons have no electrical charge and have nearly the same mass as a proton.
- Neutrons are fairly difficult to stop, and have a relatively high penetrating power.

GAS-FILLED DETECTOR

A gas-filled detector is used to detect incident radiation.

DESCRIBE the principles of operation of a gas-filled detector to include:
a. How the electric field affects ion pairs
b. How gas amplification occurs

The pulsed operation of the gas-filled detector illustrates the principles of basic radiation detection. Gases are used in radiation detectors since their ionized particles can travel more freely than those of a liquid or a solid. Typical gases used in detectors are argon and helium, although boron-triflouride is utilized when the detector is to be used to measure neutrons. Figure 5 shows a schematic diagram of a gas-filled chamber with a central electrode.

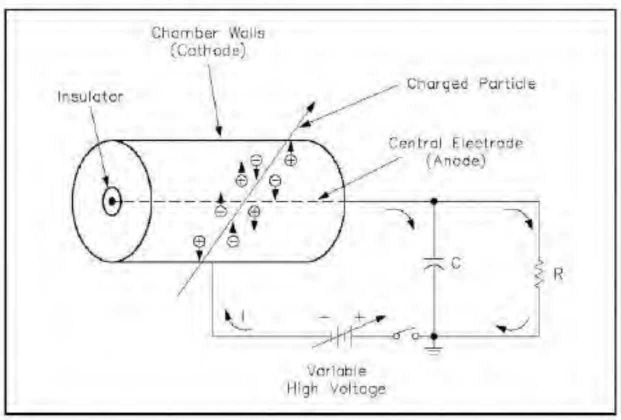

Figure 5 Schematic Diagram of a Gas-Filled Detector

The central electrode, or anode, collects negative charges. The anode is insulated from the chamber walls and the cathode, which collects positive charges. A voltage is applied to the anode and the chamber walls. The resistor in the circuit is shunted by a capacitor in parallel, so that the anode is at a positive voltage with respect to the detector wall. As a charged particle passes through the gas-filled chamber, it ionizes some of the gas (air) along its path of travel. The positive anode attracts the electrons, or negative particles. The detector wall, or cathode, attracts the positive charges. The collection of these charges reduces the voltage across the capacitor, causing a pulse across the resistor that is recorded by an electronic circuit. The voltage applied to the anode and cathode determines the electric field and its strength.

As detector voltage is increased, the electric field has more influence upon electrons produced. Sufficient voltage causes a cascade effect that releases more electrons from the cathode. Forces on the electron are greater, and its mean-free path between collisions is reduced at this threshold. Calculating the change in the capacitor's charge yields the height of the resulting pulse. Initial capacitor charge (Q), with an applied voltage (V), and capacitance (C), is given by Equation 6-4.

$$Q = CV \tag{6-4}$$

A change of charge (ΔQ) is proportional to the change in voltage (ΔV) and equals the height of the pulse, as given by Equation 6-5 or 6-6.

$$\Delta Q = C\Delta V \tag{6-5}$$

$$\Delta V = \frac{\Delta Q}{C} \tag{6-6}$$

The total number of electrons collected by the anode determines the change in the charge of the capacitor (ΔQ). The change in charge is directly related to the total ionizing events which occur in the gas. The ion pairs (n) initially formed by the incident radiation attain a great enough velocity to cause secondary ionization of other atoms or molecules in the gas. The resultant electrons cause further ionizations. This multiplication of electrons is termed gas amplification. The gas amplification factor (A) designates the increase in ion pairs when the initial ion pairs create additional ion pairs. Therefore, the height of the pulse is given by Equation 6-7.

$$\Delta V = \frac{Ane}{C} \tag{6-7}$$

where

ΔV = pulse height (volts)
A = gas amplification factor
n = initial ionizing events
e = charge of the electron (1.602×10^{-19} coulombs)
C = detector capacitance (farads)

The pulse height can be computed if the capacitance, detector characteristics, and radiation are known. The capacitance is normally about 10^{-4} farads. The number of ionizing events may be calculated if the detector size and specific ionization, or range of the charged particle, are known. The only variable is the gas amplification factor that is dependent on applied voltage.

DETECTOR VOLTAGE

Different ranges of applied voltage result in unique detection characteristics.

Given a diagram of an ion pairs collected -vs- detector voltage curve, DESCRIBE the regions of the curve to include:

a. The name of the region

b. Interactions taking place within the gas of the detector

c. Difference between the alpha and beta curves, where applicable

Applied Voltage

The relationship between the applied voltage and pulse height in a detector is very complex. Pulse height and the number of ion pairs collected are directly related. Figure 6 illustrates ion pairs collected -vs- applied voltage. Two curves are shown: one curve for alpha particles and one curve for beta particles; each curve is divided into several voltage regions. The alpha curve is higher than the beta curve from Region I to part of Region IV due to the larger number of ion pairs produced by the initial reaction of the incident radiation. An alpha particle will create more ion pairs than a beta since the alpha has a much greater mass. The difference in mass is negated once the detector voltage is increased to Region IV since the detector completely discharges with each initiating event.

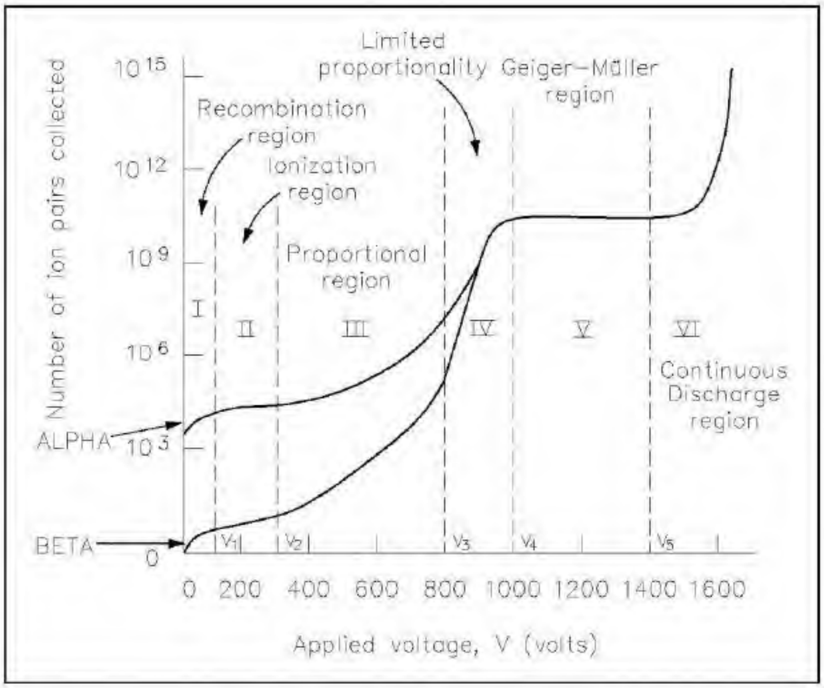

Figure 6 Ion Pairs Collected -vs- Applied Voltage

Recombination Region

In the recombination region (Region I), as voltage increases to V_1, the pulse height increases until it reaches a saturation value. At V_1, the field strength between the cathode and anode is sufficient for collection of all ions produced within the detector. At voltages less than V_1, ions move slowly toward the electrodes, and the ions tend to recombine to form neutral atoms or molecules. In this case, the pulse height is less than it would have been if all the ions originally formed reached the electrodes. Gas ionization instruments are, therefore, not operated in this region of response.

Ionization Region

As voltage is increased in the ionization region (Region II), there is no appreciable increase in the pulse height. The field strength is more than adequate to ensure collection of all ions produced; however, it is insufficient to cause any increase in ion pairs due to gas amplification. This region is called the ionization chamber region.

Proportional Region

As voltage increases to the proportional region (Region III), the pulse height increases smoothly. The voltage is sufficient to produce a large potential gradient near the anode, and it imparts a very high velocity to the electrons produced through ionization of the gas by charged radiation particles. The velocity of these electrons is sufficient to cause ionization of other atoms or molecules in the gas. This multiplication of electrons is called gas amplification and is referred to as Townsend avalanche. The gas amplification factor (A) varies from 10^3 to 10^4. This region is called the proportional region since the gas amplification factor (A) is proportional to applied voltage.

Limited Proportional Region

In the limited proportional region (Region IV), as voltage increases, additional processes occur leading to increased ionization. The strong field causes increased electron velocity, which results in excited states of higher energies capable of releasing more electrons from the cathode. These events cause the Townsend avalanche to spread along the anode. The positive ions remain near where they were originated and reduce the electric field to a point where further avalanches are impossible. For this reason, Region IV is called the limited proportional region, and it is not used for detector operation.

Geiger-Müller Region

The pulse height in the Geiger-Müller region (Region V) is independent of the type of radiation causing the initial ionizations. The pulse height obtained is on the order of several volts. The field strength is so great that the discharge, once ignited, continues to spread until amplification cannot occur, due to a dense positive ion sheath surrounding the central wire (anode). V_4 is termed the threshold voltage. This is where the number of ion pairs level off and remain relatively independent of the applied voltage. This leveling off is called the Geiger plateau which extends over a region of 200 to 300 volts. The threshold is normally about 1000 volts. In the G-M region, the gas amplification factor (A) depends on the specific ionization of the radiation to be detected.

Continuous Discharge Region

In the continuous discharge region (Region VI), a steady discharge current flows. The applied voltage is so high that, once ionization takes place in the gas, there is a continuous discharge of electricity, so that the detector cannot be used for radiation detection.

Radiation detectors are normally designed to respond to a certain type of radiation. Since the detector response can be sensitive to both energy and intensity of the radiation, each type of detector has defined operating limits based on the characteristics of the radiation to be measured. A large variety of detectors are in use in DOE facilities to detect alpha and beta particles, gamma rays, or neutrons. Some types of detectors are capable of distinguishing between the types of radiation; others are not. Some detectors only count the number of particles that enter the detector, while others are used to determine both the number and energy of the incident particles. Most detectors used in DOE facilities have one thing in common: they respond only to electrons produced in the detector. In order to detect the different types of incident particles, the particle's energy must be converted to electrons in the detector.

Gas-filled detectors are used, for the most part, to measure alpha and beta particles, neutrons, and gamma rays. The detectors operate in the ionization, proportional, and G-M regions with an arrangement most sensitive to the type of radiation being measured. Neutron detectors utilize ionization chambers or proportional counters of appropriate design. Compensated ion chambers, BF_3 counters, fission counters, and proton recoil counters are examples of neutron detectors.

PROPORTIONAL COUNTER

A proportional counter is a detector that operates in the proportional region.

DESCRIBE the operation of a proportional counter to include:

a. Radiation detection
b. Quenching
c. Voltage variations

A proportional counter is a detector which operates in the proportional region, as shown in Figure 6. Figure 7 illustrates a simplified proportional counter circuit.

To be able to detect a single particle, the number of ions produced must be increased. As voltage is increased into the proportional region, the primary ions acquire enough energy to cause secondary ionizations (gas amplification) and increase the charge collected. These secondary ionizations may cause further ionization.

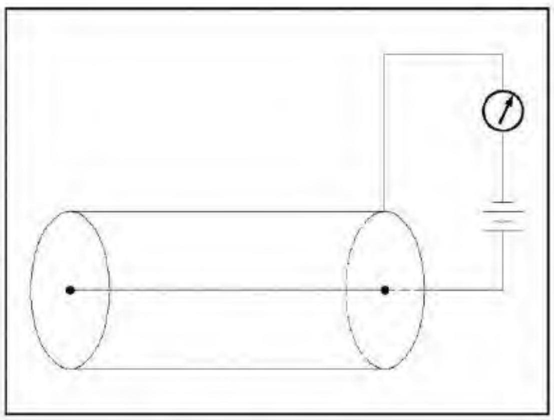

Figure 7 Proportional Counter

In this region, there is a linear relationship between the number of ion pairs collected and applied voltage. A charge amplification of 10^4 can be obtained in the proportional region. By proper functional arrangements, modifications, and biasing, the proportional counter can be used to detect alpha, beta, gamma, or neutron radiation in mixed radiation fields.

To a limited degree, the fill-gas will determine what type of radiation the proportional counter will be able to detect. Argon and helium are the most frequently used fill gases and allow for the detection of alpha, beta, and gamma radiation. When detection of neutrons is necessary, the detectors are usually filled with boron-triflouride gas.

The simplified circuit, illustrated in Figure 7, shows that the detector wall acts as one electrode, while the other electrode is a fine wire in the center of the chamber with a positive voltage applied.

Figure 8 illustrates how the number of electrons collected varies with the applied voltage.

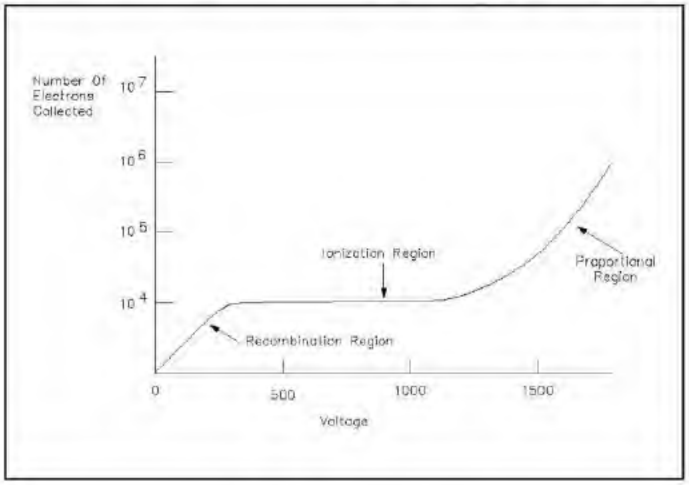

Figure 8 Gas Ionization Curve

When a single gamma ray interacts with the gas in the chamber, it produces a rapidly moving electron which produces secondary electrons. About 10,000 electrons may be formed depending on the gas used in the chamber. The applied voltage can be increased until the amount of recombination is very low. However, further increases do not appreciably increase the number of electrons collected. This region in which all 10,000 electrons are collected is the ionization region.

As applied voltage is increased above 1000 V, the number of electrons becomes greater than the initial 10,000. The additional electrons which are collected are due to gas amplification. As voltage is increased, the velocity of the 10,000 electrons produced increases. However, beyond a certain voltage, the 10,000 electrons are accelerated to such speeds that they have enough energy to cause more ionization. This phenomenon is called gas amplification.

As an example, if the 10,000 electrons produced by the gamma ray are increased to 40,000 by gas amplification, the amplification factor would be 4. Gas amplification factors can range from unity in the ionization region to 10^3 or 10^4 in the proportional region. The high amplification factor of the proportional counter is the major advantage over the ionization chamber. The internal amplification of the proportional counter is such that low energy particles (< 10 KeV) can be registered, whereas the ion chamber is limited by amplifier noise to particles of > 10 KeV energy.

Proportional counters are extremely sensitive, and the voltages are large enough so that all of the electrons are collected within a few tenths of a microsecond. Each pulse corresponds to one gamma ray or neutron interaction. The amount of charge in each pulse is proportional to the number of original electrons produced. The proportionality factor in this case is the gas amplification factor. The number of electrons produced is proportional to the energy of the incident particle.

For each electron collected in the chamber, there is a positively charged gas ion left over. These gas ions are heavy compared to an electron and move much more slowly. Eventually the positive ions move away from the positively charged central wire to the negatively charged wall and are neutralized by gaining an electron. In the process, some energy is given off, which causes additional ionization of the gas atoms. The electrons produced by this ionization move toward the central wire and are multiplied en route. This pulse of charge is unrelated to the radiation to be detected and can set off a series of pulses. These pulses must be eliminated or "quenched."

One method for quenching these discharges is to add a small amount (≈ 10%) of an organic gas, such as methane, in the chamber. The quenching gas molecules have a weaker affinity for electrons than the chamber gas does; therefore, the ionized atoms of the chamber gas readily take electrons from the quenching gas molecules. Thus, the ionized molecules of quenching gas reach the chamber wall instead of the chamber gas. The ionized molecules of the quenching gas are neutralized by gaining an electron, and the energy liberated does not cause further ionization, but causes dissociation of the molecule. This dissociation quenches multiple discharges. The quenching gas molecules are eventually consumed, thus limiting the lifetime of the proportional counter. There are, however, some proportional counters that have an indefinite lifetime because the quenching gas is constantly replenished. These counters are referred to as gas flow counters.

IONIZATION CHAMBER

The ionization chamber is a detector that operates in the ionization region.

DESCRIBE the operation of an ionization chamber to include:

a. Radiation detection
b. Voltage variations
c. Gamma sensitivity reduction

Ionization chambers are electrical devices that detect radiation when the voltage is adjusted so that the conditions correspond to the ionization region (refer to Region II of Figure 6). The charge obtained is the result of collecting the ions produced by radiation. This charge will depend on the type of radiation being detected. Ionization chambers have two distinct disadvantages when compared to proportional counters: they are less sensitive, and they have a slower response time.

There are two types of ionization chambers to be discussed: the pulse counting ionization chamber and the integrating ionization chamber. In the pulse counting ionization chamber, the pulses are detected due to particles traversing the chamber. In the integrating chamber, the pulses add, and the integrated total of the ionizations produced in a predetermined period of time is measured. The same type of ionization chamber may be used for either function. However, as a general rule, the integrating type ionization chamber is used.

Flat plates or concentric cylinders may be utilized in the construction of an ionization chamber. The flat plate design is preferred because it has a well-defined active volume and ensures that ions will not collect on the insulators and cause a distortion of the electric field. The concentric cylinder design does not have a well-defined active volume because of the variation in the electric field as the insulator is approached. Ionization chamber construction differs from the proportional counter (flat plates or concentric cylinders vice a cylinder and central electrode) to allow for the integration of pulses produced by the incident radiation. The proportional counter would require such exact control of the electric field between the electrodes that it would not be practical.

Figure 14 illustrates a simple ionization circuit consisting of two parallel plates of metal with an air space between them. The plates are connected to a battery which is connected in series with a highly sensitive ammeter.

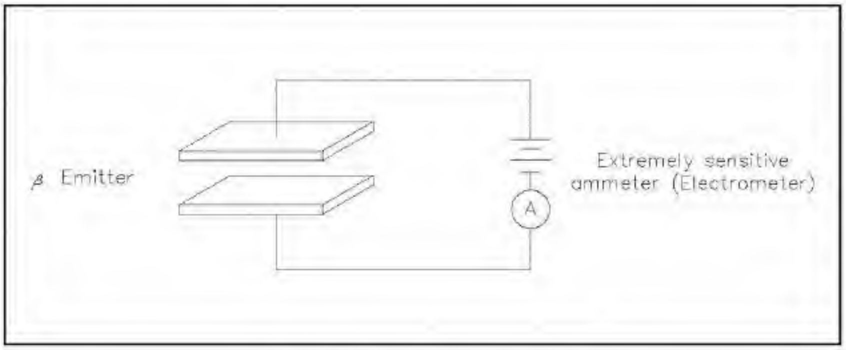

Figure 14 Simple Ionization Circuit

If a radioactive source that is an emitter of beta particles is placed near the detector, the beta particles will pass between the plates and strike atoms in the air. With sufficient energy, the beta particle causes an electron to be ejected from an atom in air. A single beta particle may eject 40 to 50 electrons for each centimeter of path length traveled. The electrons ejected by the beta particle often have enough energy to eject more electrons from other atoms in air. The total number of electrons produced is dependent on the energy of the beta particle and the gas between the plates of the ionization chamber.

In general, a 1 MeV beta particle will eject approximately 50 electrons per centimeter of travel, while a 0.05 MeV beta particle will eject approximately 300 electrons. The lower energy beta ejects more electrons because it has more collisions. Each electron produced by the beta particle, while traveling through air, will produce thousands of electrons. A current of 1 micro-ampere consists of about 10^{12} electrons per second.

If 1 volt is applied to the plates of the ionization chamber shown in Figure 14, some of the free electrons will be attracted to the positive plate of the detector. This attraction is not strong because 1 volt does not create a strong electric field between the two plates. The free electrons will tend to drift toward the positive plate, causing a current to flow, which is indicated on the ammeter. Not all of the free electrons will make it to the positive plate because the positively charged atoms that resulted when an electron was ejected may recapture other free electrons. Therefore, the ammeter will register only a fraction of the number of free electrons between the plates.

When the voltage is increased, the free electrons are more strongly attracted to the positive plate. They will move toward the positive plate more quickly and will have less opportunity to recombine with the positive ions. Figure 15 shows a plot of the number of electrons measured by the ammeter as a function of applied voltage.

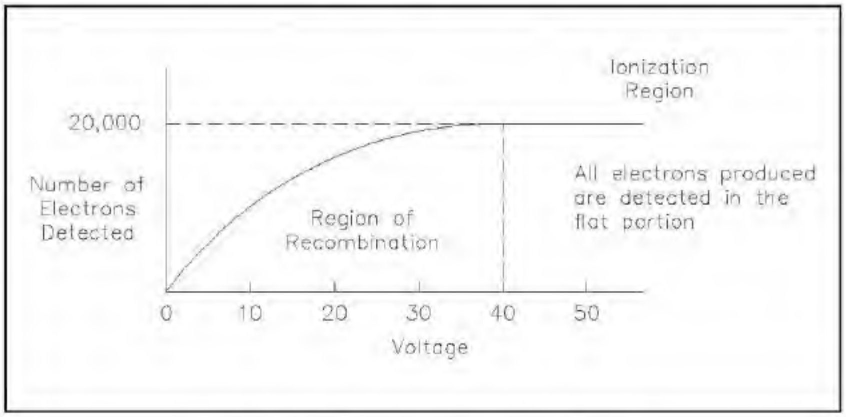

Figure 15 Recombination and Ionization Regions

At zero voltage, no attraction of electrons between the plates occurs. The electrons will eventually recombine, so there is no current flow. As the applied voltage is increased, the positive plate will begin to attract free electrons more strongly, and a higher percentage will reach the positive plate. As the voltage is increased further, a point will be reached in which all of the electrons produced in the chamber will reach the positive plate. Any further increase in voltage has no effect on the number of electrons collected.

The simple ionization chamber shown in Figure 14 can also be utilized for the detection of gamma rays. Since the ammeter is sensitive only to electrons, gamma rays must interact with the atoms in air between the plates to release electrons. The gamma rays interact by compton scattering, photoelectric effect, or pair production. Each of these interactions causes some, or all, of the energy of the incident gamma rays to be converted into the kinetic energy of the ejected electrons. The ejected electrons move at very high speeds and cause other electrons to be ejected from their atoms. All of these electrons can be collected by the positively charged plate and measured by the ammeter.

The plates in an ionization chamber are normally enclosed in metal, as shown by Figure 16.

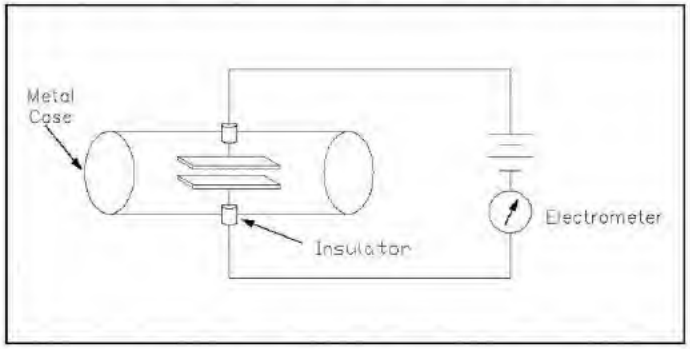

Figure 16 Ionization Chamber

This metal chamber serves to shield the plates from outside electric fields and to contain the air or other gas. Gamma rays have very little trouble in penetrating the metal walls of the chamber. Beta particles and alpha particles, however, are stopped by the metal wall. For alpha and beta particles to be detected, some means must be provided for a thin wall or "window." This window must be thin enough for the alpha and beta particles to penetrate. However, a window of almost any thickness will prevent an alpha particle from entering the chamber.

Neutrons can also be detected by an ionization chamber. As we already know, neutrons are uncharged; therefore, they cause no ionizations themselves. If the inner surface of the ionization chamber is coated with a thin coat of boron, the following reaction can take place.

$$^{10}_{5}B + ^{1}_{0}n \rightarrow ^{7}_{3}Li^{+++} + ^{4}_{2}He^{++} + 5e^{-}$$

A neutron is captured by a boron atom, and an energetic alpha particle is emitted. The alpha particle causes ionization within the chamber, and ejected electrons cause further secondary ionizations.

Another method for detecting neutrons using an ionization chamber is to use the gas boron trifluoride (BF_3) instead of air in the chamber. The incoming neutrons produce alpha particles when they react with the boron atoms in the detector gas. Either method may be used to detect neutrons in nuclear reactor neutron detectors.

When using an ionization chamber for detecting neutrons, beta particles can be prevented from entering the chamber by walls thick enough to shield out all of the beta particles. Gamma rays cannot be shielded from the detector; therefore, they always contribute to the total current read by the ammeter. This effect is not desired because the detector responds not only to neutrons, but also to gamma rays. Several ways are available to minimize this problem.

Discrimination is possible because the ionizations produced by the alpha particles differ in energy levels from those produced by gamma rays. A 1 MeV alpha particle moving through the gas loses all of its energy in a few centimeters. Therefore, all of the secondary electrons are produced along a path of only a few centimeters. A 1 MeV gamma ray produces a 1 MeV electron, and this electron has a long range and loses its energy over the entire length of its range. If we make the sensitive volume of the chamber smaller without reducing the area of the coated boron, the sensitivity to gamma rays is reduced.

Figure 17 illustrates how the chamber may be modified to accomplish this reduction.

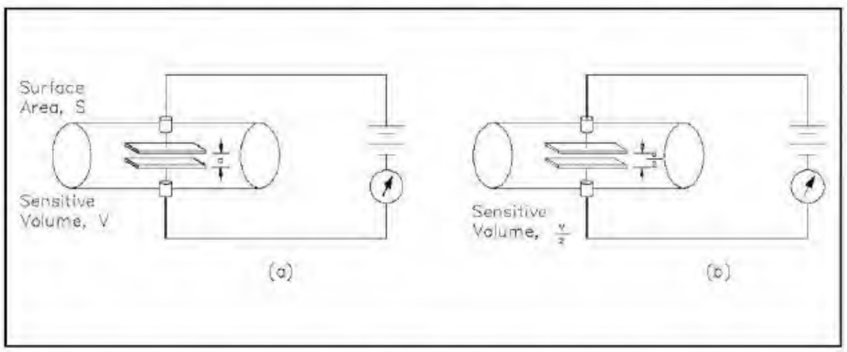

Figure 17 Minimizing Gamma Influence by Size and Volume

In Figure 17(b) there is half as much gas in the sensitive volume as in the chamber in Figure 17(a). As a result, gamma rays have only half as much gas to interact with; therefore, half the number of electrons are produced. The area which is boron-coated has not changed, and both chambers produce the same number of neutron-induced alpha particles. Also, the gamma ray-induced electrons produce fewer ionizations because the range of these electrons is longer than the dimensions of the sensitive volume. The range of neutron-induced alpha particles is short, and all of the energy will be dissipated within the sensitive volume, even when the volume is smaller.

Gamma interference can also be minimized by reducing the pressure of the gas inside the chamber. The reduction in pressure reduces the number of atoms within the sensitive volume and has the same effect as reducing the volume.

Ionization chamber sensitivity to gamma rays can also be reduced by increasing chamber sensitivity to neutrons. This is accomplished by increasing the boron-coated area, as shown in Figure 18. Both ionization chambers shown in Figure 18 have the same sensitive volume.

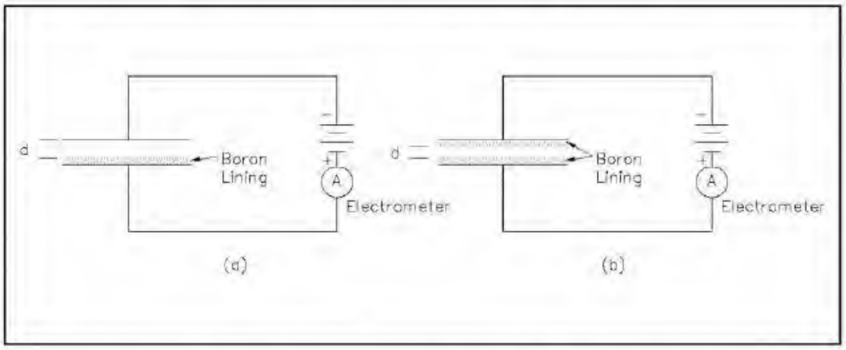

Figure 18 Minimizing Gamma Influence with Boron Coating Area

The ionization chamber in Figure 18(b) has twice the boron area as the ionization chamber in Figure 18(a). The result is that more neutron-induced alpha particles are produced, and neutron sensitivity is increased. Ionization chambers supplied commercially are designed to minimize gamma sensitivity by both of the techniques described previously. Gamma sensitivity can be minimized but not eliminated. For reactors operating near peak power, neutrons are the dominant radiation, and almost all of the current is due to neutrons. These chambers are used at high reactor powers and are referred to as uncompensated ion chambers. The uncompensated ion chamber is not suitable for use at intermediate or low power levels because the gamma response at these power levels can be significant compared to the neutron response.

COMPENSATED ION CHAMBER

Gamma compensation is required at intermediate reactor power levels to ensure accurate power reading.

DESCRIBE how a compensated ion chamber compensates for gamma radiation.

Compensating for the response to gamma rays extends the useful range of the ionization chamber. Compensated ionization chambers consist of two separate chambers; one chamber is coated with boron, and one chamber is not. The coated chamber is sensitive to both gamma rays and neutrons, while the uncoated chamber is sensitive only to gamma rays. Instead of having two separate ammeters and subtracting the currents, the subtraction of these currents is done electrically, and the net output of both detectors is read on a single ammeter. If the polarities are arranged so that the two chambers' currents oppose one another, the reading obtained from the ammeter indicates the difference between the two currents. One plate of the compensated ion chamber is common to both chambers; one side is coated with boron, while the other side is not.

Figure 19 shows the basic circuitry for a compensated ion chamber.

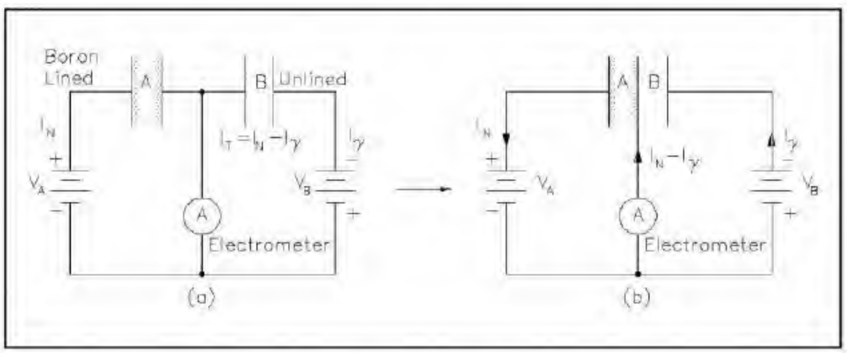

Figure 19 Compensated Ion Chamber

The boron coated chamber is referred to as the working chamber; the uncoated chamber is called the compensating chamber. When exposed to a gamma source, the battery for the working chamber will set up a current flow that deflects the meter in one direction. The compensating chamber battery will set up a current flow that deflects the meter in the opposite direction. If both chambers are identical, and both batteries are of the same voltage, the net current flow is exactly zero. Therefore, the compensating chamber cancels the current due to gamma rays.

The two chambers of a compensated ion chamber are never truly identical; in fact, they are often purposely constructed in different shapes. The chambers are normally constructed as concentric cylinders, as illustrated in Figure 20.

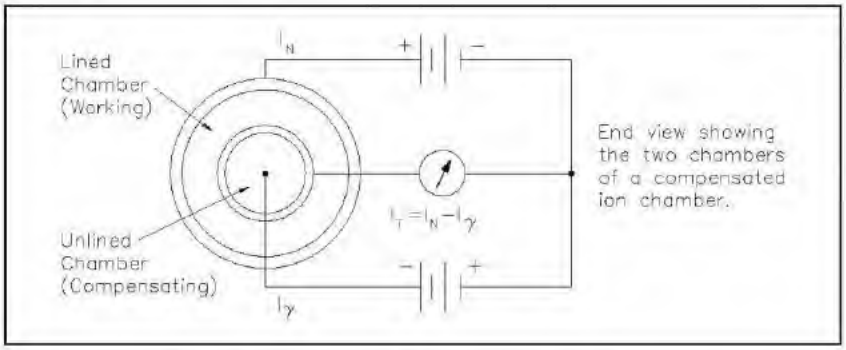

Figure 20 Compensated Ion Chamber with Concentric Cylinders

The use of concentric cylinders has an advantage because both chambers are exposed to nearly the same radiation field. Even though the chambers are not identical, proper selection of the operating voltage eliminates the gamma current. Working chamber operating voltage is given by the manufacturer and is selected to cause operation on the flat portion of the response curve, where very little recombination occurs. If working chamber voltage is increased to operating voltage, and compensating voltage is left at zero, the measured current will be due to gammas only in the working chamber. For this reason, compensating voltage is set while the reactor is shutdown (a minimum number of neutrons are present).

As the compensating chamber voltage is raised, the measured current will decrease as more of the current from the working chamber is canceled by the current from the compensating chamber. Eventually, the voltage becomes large enough so that the two currents cancel. When the currents cancel, the chamber is said to be 100% compensated, and the measured current is zero. At 100% compensation, the detector will respond to neutrons alone.

The compensating chamber usually has a slightly larger sensitive volume than the working chamber. Increasing the compensating current to a value greater than the working chamber current results in a net negative current. In this condition, the chamber is said to be overcompensated. The compensating chamber cancels too much current from the working chamber, and the meter reads low. In this case, the compensating chamber cancels out all of the gamma current and some of the neutron current.

Percent compensation of a compensated ion chamber gives the percentage of the gamma rays which are canceled out. Percent compensation may be calculated based on measured current, when the detector is exposed to gamma rays only as given in Equation 6-9.

$$\text{Percent Compensation} = 1 - \frac{I_{\text{measured}}}{I_{\text{operating}}} \times 100\% \qquad (6\text{-}9)$$

where

$I_{measured}$ = measured current (milliamps)
$I_{operating}$ = measured current with compensating voltage OFF (milliamps)

If measured current is zero, then percent compensation is 100%. If measured current is positive, the percent compensation is less than 100%, and the chamber is undercompensated. If the measured current is negative, the percent compensation is greater than 100%, and the chamber is overcompensated.

The ionization chamber compensation curve, Figure 21, is a plot of the percent compensation versus compensating voltage. This compensation curve must be plotted prior to using a compensated ion chamber.

In ideal situations, compensated ion chambers operate at 100% compensation, and indicated current is due to neutrons. Small changes in compensating voltage change the percent compensation.

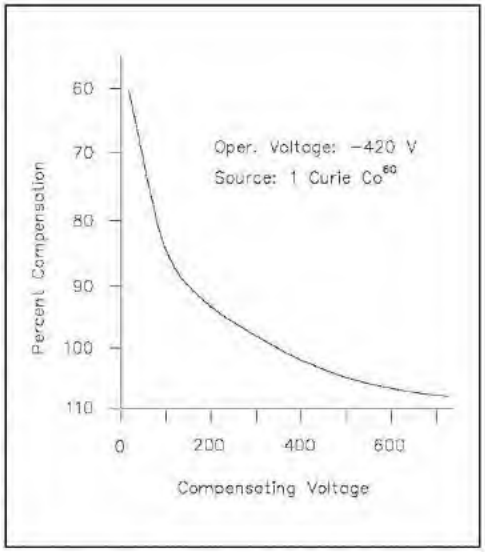

Figure 21 Typical Compensation Curve

The consequences of operating with an overcompensated or undercompensated chamber are important. The purpose of nuclear instrumentation is to detect and measure neutron level, which is the direct measure of core power. If the compensating voltage is set too high, or overcompensated, some neutron current, as well as all of the gamma current, is blocked, and indicated power is lower than actual core power. If compensating voltage is set too low, or undercompensated, not all of the gamma current is blocked, and indicated power is higher than actual core power. At high power, gamma flux is relatively small compared to neutron flux, and the effects of improper compensation may not be noticed. It is extremely important, however, that the chamber be properly compensated during reactor startup and shutdown.

GEIGER-MÜLLER DETECTOR

The Geiger-Müller detector is a radiation detector which operates in the G-M region.

DESCRIBE the operation of a Geiger-Müller (G-M) detector to include:

a. Radiation detection

b. Quenching

c. Positive ion sheath

The Geiger-Müller or G-M detector is a radiation detector that operates in Region V, or G-M region, as shown on Figure 23. G-M detectors produce larger pulses than other types of detectors. However, discrimination is not possible, since the pulse height is independent of the type of radiation. Counting systems that use G-M detectors are not as complex as those using ion chambers or proportional counters.

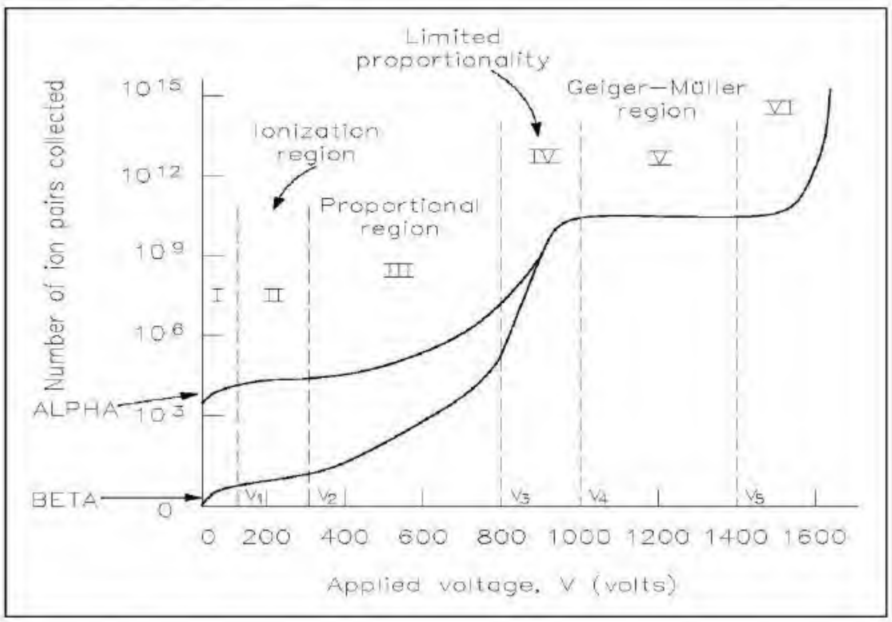

Figure 23 Gas Ionization Curve

The number of electrons collected by a gas-filled detector varies as applied voltage is increased. Once the voltage is increased beyond the proportional region, another flat portion of the curve is reached; this is known as the Geiger-Müller region. The Geiger-Müller region has two important characteristics:

- The number of electrons produced is independent of applied voltage.
- The number of electrons produced is independent of the number of electrons produced by the initial radiation.

This means that the radiation producing one electron will have the same size pulse as radiation producing hundreds or thousands of electrons. The reason for this characteristic is related to the way in which electrons are collected.

When a gamma produces an electron, the electron moves rapidly toward the positively charged central wire. As the electron nears the wire, its velocity increases. At some point its velocity is great enough to cause additional ionizations. As the electrons approach the central wire, the additional ionizations produce a larger number of electrons in the vicinity of the central wire.

As discussed before, for each electron produced there is a positive ion produced. As the applied voltage is increased, the number of positive ions near the central wire increases, and a positively charged cloud (called a positive ion sheath) forms around the central wire. The positive ion sheath reduces the field strength of the central wire and prevents further electrons from reaching the wire. It might appear that a positive ion sheath would increase the effect of the positive central wire, but this is not true; the positive potential is applied to the very thin central wire that makes the strength of the electric field very high. The positive ion sheath makes the central wire appear much thicker and reduces the field strength. This phenomenon is called the detector's space charge. The positive ions will migrate toward the negative chamber picking up electrons. As in a proportional counter, this transfer of electrons can release energy, causing ionization and the liberation of an electron. In order to prevent this secondary pulse, a quenching gas is used, usually an organic compound.

The G-M counter produces many more electrons than does a proportional counter; therefore, it is a much more sensitive device. It is often used in the detection of low-level gamma rays and beta particles for this reason. Electrons produced in a G-M tube are collected very rapidly, usually within a fraction of a microsecond. The output of the G-M detector is a pulse charge and is often large enough to drive a meter without additional amplification. Because the same size pulse is produced regardless of the amount of initial ionization, the G-M counter cannot distinguish radiation of different energies or types. This is the reason G-M counters are not adaptable for use as neutron detectors. The G-M detector is mainly used for portable instrumentation due to its sensitivity, simple counting circuit, and ability to detect low-level radiation.

MISCELLANEOUS DETECTORS

Four other types of radiation detectors are the self-powered neutron detector, wide range fission chamber, flux wire, and photographic film.

DESCRIBE how the following detect neutrons:
a. Self-powered neutron detector
b. Wide range fission chamber
c. Flux wire

DESCRIBE how a photographic film is used to measure the following:
a. Total radiation dose
b. Neutron dose

Self-Powered Neutron Detector

In very large reactor plants, the need exists to monitor neutron flux in various portions of the core on a continuous basis. This allows for quick detection of instability in any section of the core. This need brought about the development of the self-powered neutron detector that is small, inexpensive, and rugged enough to withstand the in-core environment. The self-powered neutron detector requires no voltage supply for operation. Figure 29 illustrates a simplified drawing of a self-powered neutron detector.

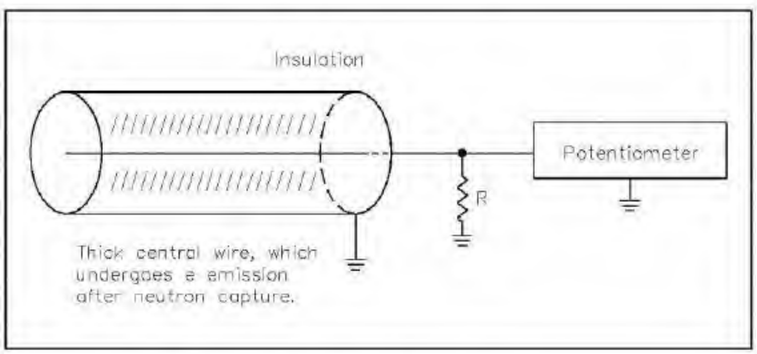

Figure 29 Self-Powered Neutron Detector

The central wire of a self-powered neutron detector is made from a material that absorbs a neutron and undergoes radioactive decay by emitting an electron (beta decay). Typical materials used for the central wire are cobalt, cadmium, rhodium, and vanadium. A good insulating material is placed between the central wire and the detector casing. Each time a neutron interacts with the central wire it transforms one of the wire's atoms into a radioactive nucleus. The nucleus eventually decays by the emission of an electron. Because of the emission of these electrons, the wire becomes more and more positively charged. The positive potential of the wire causes a current to flow in resistor, R. A millivoltmeter measures the voltage drop across the resistor. The electron current from beta decay can also be measured directly with an electrometer.

There are two distinct advantages of the self-powered neutron detector: (a) very little instrumentation is required--only a millivoltmeter or an electrometer, and (b) the emitter material has a much greater lifetime than boron or U^{235} lining (used in wide range fission chambers).

One disadvantage of the self-powered neutron detector is that the emitter material decays with a characteristic half-life. In the case of rhodium and vanadium, which are two of the most useful materials, the half-lives are 1 minute and 3.8 minutes, respectively. This means that the detector cannot respond immediately to a change in neutron flux, but takes as long as 3.8 minutes to reach 63% of steady-state value. This disadvantage is overcome by using cobalt or cadmium emitters which emit their electrons within 10^{-14} seconds after neutron capture. Self-powered neutron detectors which use cobalt or cadmium are called prompt self-powered neutron detectors.

Wide Range Fission Chamber

Fission chambers use neutron-induced fission to detect neutrons. The chamber is usually similar in construction to that of an ionization chamber, except that the coating material is highly enriched U^{235}. The neutrons interact with the U^{235}, causing fission. One of the two fission fragments enters the chamber, while the other fission fragment embeds itself in the chamber wall.

One advantage of using U^{235} coating rather than boron is that the fission fragment has a much higher energy level than the alpha particle from a boron reaction. Neutron-induced fission fragments produce many more ionizations in the chamber per interaction than do the neutron-induced alpha particles. This allows the fission chambers to operate in higher gamma fields than an uncompensated ion chamber with boron lining. Fission chambers are often used as current indicating devices and pulse devices simultaneously. They are especially useful as pulse chambers, due to the very large pulse size difference between neutrons and gamma rays. Because of the fission chamber's dual use, it is often used in "wide range" channels in nuclear instrumentation systems. Fission chambers are also capable of operating over the source and intermediate ranges of neutron levels.

Activation Foils and Flux Wires

Whenever it is necessary to measure reactor neutron flux profiles, a section of wire or foil is inserted directly into the reactor core. The wire or foil remains in the core for the length of time required for activation to the desired level. The cross-section of the flux wire or foil must be known to obtain an accurate flux profile. After activation, the flux wire or foil is rapidly removed from the reactor core and the activity counted.

Activated foils can also discriminate energy levels by placing a cover over the foil to filter out (absorb) certain energy level neutrons. Cadmium covers are typically used for this purpose. The cadmium cover effectively filters out all of the thermal neutrons.

Photographic Film

Photographic film may be utilized in x-ray work and dosimetry. The film tends to darken when exposed to radiation. This general darkening of the film is used to determine overall radiation exposure. Neutron scattering produces individual proton recoil tracks. Counting the tracks yields the film's exposure to fast neutrons. Filters are used to determine the energy and type of radiation. Some typical filters used are aluminum, copper, cadmium, or lead. These filters provide varying amounts of shielding for the attenuation of different energies. By comparing the exposure under the different filters, an approximate spectrum is determined.